STAFF SUMMARY SHEET

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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Cadets Christopher S. Keranen, Patrick A. Lobo, Jason A. Douglas, Stephaney N. Saari, Lt Col Thomas Joslyn (DFAN)

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3. DISCUSSION.

4. VIEWS OF OTHERS.

5. RECOMMENDATION. Department Head or designee reviews as sub ... rity. Coordination indicates the document is suitable for public release. Suitab ... jeopardizing DoD interests, and accurately portraying official policy [Re ... e originator (author). Compliance with AFI 35-102 is mandatory.

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Col Kraus

Thomas B. Joslyn, O-5, DFAN
Associate Professor

1 Tab
1. Abstract

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Innovative and Cost Effective Remediation of Orbital Debris

TEAM MEMBERS: Christopher S. Keranen, Patrick A. Lobo, Jason A. Douglas, Stephaney N. Saari
Team Advisor: Dr. Thomas B. Joslyn
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Introduction

More than a million objects, large enough to threaten operational spacecraft, are believed to reside in low Earth orbit (LEO) and this value is expected to increase significantly in the next decades.[1] The resulting hazard to operational spacecraft could render certain LEO altitudes unusable, particularly above 500 km where atmospheric drag is ineffective for removing orbital debris. Certain objects, such as spent rocket stages and large defunct satellites, have the potential to create thousands of smaller bodies through impacts with other objects, some too small to track.[2]

Dr. J. C. Liou from the National Aeronautics and Space Administration (NASA) Orbital Debris Program Office prioritized the hazard posed by thousands of objects in orbit as a function of object mass and collision probability. The study concluded that the breakup of a just three of the 500 highest priority objects would lead to collisions with other objects and debris populations that would render certain altitudes too hazardous for satellite operations. NASA researchers determined that the removal of just five high-priority objects each year would likely prevent anticipated growth in the debris population.[3]

The growing population of orbital debris poses a real and growing threat of impact with active spacecraft that has caused and will increasingly cause millions of dollars in damage to operational spacecraft. In the coming decades debris impacts are also likely to degrade national security, adversely affect the economy, and threaten the lives on manned spacecraft. Population growth in the next 50 years could be gradual or could yield concentrations high enough to render parts of Low Earth Orbit (LEO) unusable and transit through these regions hazardous. Of particular concern is the region of LEO between 600 and 1000 km where numerous large and fragile rocket bodies reside. At these altitudes, objects incur very little atmospheric drag and can remain in orbit for centuries. These rocket bodies are effectively ticking time bombs that, when hit, can create thousands of projectiles, each of which could potentially impact other rocket bodies.

In an effort to mitigate the threat posed by orbital debris, researchers at the United States Air Force Academy (USAFA) have developed the StreamSat concept for removal of objects from LEO. StreamSat is an innovative spacecraft that projects small clouds of liquid droplets into the path of on-coming debris for impact and transfer of momentum. Droplets are vaporized during the impact and the object is slowed and its orbit perigee lower and, ultimately causing reentry in the atmosphere. A single StreamSat can remove dozens of objects from orbit with little or no maneuvering between remediation events. StreamSat technology also has the ability to alter the trajectory of an object that is nearing reentry to affect a controlled reentry into an ocean and avoid possible impact with populated areas. Since the United States is liable for damage cause by objects that it launches into orbit, this capability provide a method for avoiding costly reentry incidents and possible loss of life on the ground. The possibility even exists for altering the path of asteroids or ballistic projectiles threatening populated areas, though this has not yet been analyzed.

To date, most remediation methods proposed require a separate intercepting spacecraft for each object that is targeted for remediation. Some concepts call for small spacecraft to rendezvous with objects and attach drag producing devices and One method proposed calls for a laser that can eliminate multiple objects with a single spacecraft, however, this requires significant amounts of power and a very large spacecraft to generate and store that power.

Although this product has potential commercial value as a method of protecting operational spacecraft, the main customers are expected to be domestic and foreign government agencies since they operate some of the most critical spacecraft and self-insure their spacecraft. In addition, government space agencies are generally the most fiscally capable groups concerned with the effects of space debris on their assets. The market for space debris remediation is small and not yet fully developed. There are currently no companies that have a demonstrated method of remediation; however, the European Space Agency (ESA) has made a request for proposals from companies interested in performing remediation missions.[4] At least one company, Swiss Space Systems, has a plan to use a small spacecraft to rendezvous with and attach to a derelict spacecraft and lower the orbit for a controlled reentry.***** This approach faces significant challenges associated with attaching to an uncontrolled object without damaging the object and can only remove on object per remediation spacecraft launched. Like StreamSat, the competitors in this market of space debris remediation are not in the production stage yet. However, there are no other proposed remediation methods that can remove hazardous large objects in such an efficient and economical manner.

Technical Analysis

Most of StreamSat's spacecraft subsystems do not require any technical advances. In particular, communication, data handling and storage, thermal control, power generation and storage, and spacecraft structure can be satisfied with off-the-shelf components. StreamSat will need a relatively high degree of pointing control and knowledge. Placing droplets on a $1 m^2$ target over a distance of 20 km requires a pointing accuracy of 10.3 arc seconds. Existing small satellite reaction wheel control systems have demonstrated this accuracy in-flight. Electrospray thrusters, demonstrated at the Air Force Academy and elsewhere, can also produce the impulse bit needed to maintain such pointing accuracy. Droplet streams can be produced from separate sites on the surface of a spacecraft in a

manner that minimizes the amount of disturbance torque imparted to the spacecraft. Analysis of a very small spacecraft (3U CubeSat) producing dozens of high-speed streams simultaneously show that existing attitude control systems provide slow rate to compensate for a malfunctioning stream generator located as far from the spacecraft center of gravity as possible (15 cm). Larger spacecraft will respond more slowly to a disturbance torque of this nature and can also be controlled within 10.3 arc seconds with existing attitude control systems.

Essential to the prospect of intercepting objects with droplets is accurate projection through space. There are several sources of pointing error including the control fidelity of the projecting spacecraft, knowledge of targeted object position, environmental forces, and limitations in machining droplet stream generators. Researchers at the University of Southern California looked at the accuracy of droplet stream generators in the 1980s as part of a program called the Liquid Droplet Radiator (LDR). [5] They demonstrated droplet dispersion of less than 1 micro radian for some generators and devised an instrument for measuring the dispersion accuracy of generators in a long vacuum chamber prior to flight in space.[6] The ability to test the natural dispersion angle of droplet generators prior to flight allows for selection of flight hardware with demonstrated accuracy better than 1 micro radian. Spacecraft attitude control introduces more pointing accuracy error, but can be nearly two orders of magnitude better. Taken together, attitude control and droplet generator pointing error can be limited to less than one micro radian using existing technology and techniques.

During transit, external forces will alter the path of droplets and could cause the target to be missed unless models can accurately predict these forces and compensate for them. Forces acting on droplets include Coulomb forces, drag, solar radiation pressure, and Lorentz forces. Coulomb forces are directly proportional to the charge developed by droplets and exponentially proportional to the distance between droplets. Therefore, it is necessary for neighboring droplets to have known size so that the magnitude and effects of coulomb forces can be predicted and corrected for. If charge can be predicted accurately, clouds of droplet streams can be generated in a manner that optimizes mass density of the cloud at impact with the target. The ionic liquid BMIM-BF_4 is proposed as the momentum transfer medium precisely because of its relatively high conductivity and low predicted charge, relative to the ambient plasma. Computer modeling of droplet charging in space has been performed at the University of Colorado[7] and partially validated by experiments in vacuum, but the amount to which free-flying liquid will charge in space should be validated through experimentation in space.

If droplets miss the target, they will tend to drift apart due to the action of electrostatic forces between charged droplets. Thus, if a droplet cloud misses the intended target, the cloud will expand with time, reducing the mass density of the cloud to significantly lower levels. The effect of an unintended impact of a small number of widely spaced droplets with an operational spacecraft would be to impart a relatively insignificant amount of momentum to that spacecraft. Testing of high velocity impacts with Aluminum at the USAF Academy has shown no significant effects on this material and that the droplets are vaporized during the impact. Long term exposure of BMIM-BF_4 to radiation has been shown to cause an increase in absorptivity and is expected to eventually lead to evaporation.[8,9] The addition of nanoparticles of Carbon to ionic liquids has been shown to increase absorptivity. Also, the addition of carbon nanoparticles has been shown to increase absorptivity of reduce the life of droplets in space by accelerating vaporization caused by solar heating.[10]

Before intercept of spacecraft with droplet streams can be demonstrated, it is necessary to refine predictive models of droplet charging by producing droplets in space and measuring their charge. As a precursor to an operational orbital debris intercept spacecraft, a demonstrator spacecraft called StreamDemoSat is proposed that will measure the effectiveness and determine the limitations of droplet streams to transfer momentum through a series of experiments. In these experiments, droplets will be transferred from the end of a boom, through an electric field, and to an impact location sensor on the spacecraft. Results will be used to refine algorithms that predict drag, Lorentz, solar radiation pressure, and Coulomb forces that will alter the path of transiting droplets. StreamDemoSat could also conduct technology demonstration experiments with Electrospray thrusters to evaluate their attitude and orbit control capabilities. Electrospray thrusters can use BMIM-BF_4 as propellant and can use the same supply of liquid used for momentum transfer as fuel for the orbit and attitude control system.[11] StreamDemoSat could also include an optical or infrared sensor for use in detecting objects and refining their orbit more accurately than is possible with ground-based sensors alone.

There are several key performance parameters that can be improved with evaluation, on-orbit, prior to projecting droplet streams into the path of objects. Knowledge of droplet charge will be used to predict the magnitude of Lorentz and Coulomb forces acting on charged droplets and determine the minimum separation distance between droplets for various propagation distances. Charge knowledge will also allow the force of drag to be determined by removing the charge-induced Lorentz forces from the sum of forces determined by on-orbit tests. Calculations and testing indicate that by refining droplet flight path predictive models, the risk of missing a 1 square meter targeted object of known position can be limited to less than a single miss per one million droplets transferred.

In the event that a droplet misses the target the danger posed to other spacecraft is limited for several reasons. First, the orbital life of a droplet is significantly shorter than that of a typical spacecraft due to a droplet's lower ballistic coefficient and increased deceleration. Second, the droplet is expected to remain in a liquid state, even in a typical eclipse period so that a collision with the droplet is expected to vaporize the droplet leaving little if any residue on glass or other clear materials. Third, droplets are expected to drift apart over time due to small variations in their initial velocity and mass. This means that it is unlikely that a random collision with a large number of droplets will occur and, therefore, very little momentum transfer is likely to be imparted during a random collision.

Silicon oils and ionic liquids have very low vapor pressure and are liquid at the temperatures expected during droplet transit. The ionic liquid BMIM-BF4 has a wide range of temperatures at which it remains a liquid and is chemically stable, even when exposed to high energy particles and other forms of radiation. This fluid has undergone testing at USAFA showing it will not evaporate in vacuum until reaching at least 300°C. It will also be necessary to account for the interactions between individual droplets in parallel droplet streams. If the droplets are fired too closely to one another, Coulomb forces between droplets will repel each other and cause some droplets to miss the target.

Analysis shows that free-flying droplets will not freeze during typical LEO eclipse periods. Liquid droplets are less likely to damage a spacecraft than solid droplets are since they flatten and distribute their force of momentum over a larger area than solid droplets. Liquid droplets that impact spacecraft at speeds greater than 1200m/s are expected to vaporize during the impact. In the event that droplets miss the targeted object they are predicted to evaporate over the course of a few years (depending on absorptivity changes) and pose little threat to operational spacecraft. The ballistic coefficient of free-flying droplets is much lower than typical spacecraft and atmospheric drag will de-orbit droplets more quickly than larger objects. Research indicates that droplets can be darkened to increase solar heating and raise droplet temperatures above their evaporation point and shorten their expected life to less than one month.

Market Analysis

This is a quickly emerging market. Some companies have projected that their product will be ready for launch and in-space tested as early as 2018.[12] Essentially, the company that emerges at the forefront of this market will enter the market in a timely manner, be comparatively more affordable, and more efficient. StreamSat has not yet tested the product in space, but has conducted significant analysis and hardware development. StreamSat utilizes outside engineering manufacturing companies to develop the product, and in house engineering for final design specifications. Facilities at the United States Air Force Academy have been used to test components of the product both in and out of vacuum to simulate the space environment. Prospectively, this product has moderately high potential, as seen in Table 1.

Industry Attractiveness Assessment		
Factor	**Value**	**Potential**
Number of Competitors	Few	Moderate
Age of Industry	Young	High
Growth Rate of Industry	Moderate	Moderate
Average Net Income of Firms	N/A	N/A
Degree of Industry Concentration	Fragmented	High
Stage of Industry Life Cycle	Growth Phase	Moderate
Importance of product/service	High	High
Extent to which trends are moving in favor of industry	Medium	Moderate
Number of new products emerging in the industry	Medium	Moderate
Long-term Prospects	Strong	High

Table 1. Assessment of Industry Attractiveness

In the United States, the Department of Defense (DoD) is charged with tracking objects in space and NASA is tasked with evaluating methods for ameliorating the problem of orbital debris . The effectiveness of StreamSat would be significantly enhanced by timely updates of high-priority object orbit information from the DoD's network of tracking sensors. Routine control of StreamSat can be performed by the U.S. Air Force Academy (USAFA) ground station or a similarly equipped ground station. During actual debris intercepts, other ground stations may be needed to provide StreamSat with timely object orbit information prior to the intercept. Such timely updates could be provided by ground stations in other nations or U.S. stations located around the world. Design, development, assembly, integration and most testing could be conducted at the Air Force Academy; however, USAFA has a full schedule for development of FalconSAT 6 and 8. To begin development of StreamSat in a timely manner, collaboration with another company, university, or organization is required. The target market is government and space agencies, Table 2 shows Target Market Attractiveness Assessment. This table suggests that this product has moderate potential; however, once the market fully emerges we believe that many of the "moderate" categories will become "high potential" categories.

Target Market Attractiveness Assessment		
Factor	**Value**	**Potential**
Number of competitors in target market	Few	Moderate
Growth rate of firms in the target market	N/A	N/A
Average net income for firms in target market	N/A	N/A
Methods for generating revenue	Clear	High
Ability to create "barriers to entry" for competitors	May or may not be able to create	Moderate
Degree to which customers feel satisfied by the current offerings	Dissatisfied	High
Potential to employ low cost guerilla and/or buzz marketing	Moderate	Moderate

techniques		
Excitement surrounding new product/service offerings	Moderate	Moderate

Table 2. Market Attractiveness Assessment

Development is estimated to take 36-42 months using the same development schedule currently used for other spacecraft produced by USAFA. This schedule could be accelerated considerably with a management system that is not tied to a semester system where the workforce turns over every year. The spacecraft is expected to operate for 2-3 years before depleting its supply of ionic liquid. Once fluid is depleted, the StreamSat can still provide object tracking information to the space operations community (if so equipped). At the end of its operational lifetime the spacecraft will use a reserve of ionic liquid as propellant to expedite its own deorbit with on-board Electrospray thrusters (if so equipped).

Industry Analysis

The global satellite industry is currently a $189.5 billion industry with a growth rate of 10% since 2001. The average satellite costs $99 million with an average launch cost of $51 million. Companies that utilize satellites in space spend millions to insure their satellites with the average coverage costing 8%-15% of the total cost of the satellite. The profitability of space for communications, GPS, television, and other technological trends is another reason why the removal of space debris affects many government and private companies. We assessed the need for orbital debris remediation and concluded that the need is both of interest to the industry at large and being pursued by companies and government agencies in several countries. This assessment is summarized in Table 3.

Market Timeliness Assessment		
Factor	**Value**	**Potential**
Buying mood of customers	Moderate	High
Momentum of the Market	Moderate	Moderate
Need for a new firm with your offering	High	High
Extent to which business and environmental trends are moving in favor of the target market	High	High
Recent or planned entrance of large firms	Large firms entering the market	Low

Table 3. Analysis of Timeliness of Entry into the Orbital Debris Market

Overall, advances in electronics and launch technologies are leading to a new class of smaller, cheaper, and lower-flying satellites. If government and private space agencies wish to pursue capabilities to launch more satellites into LEO in the future, it is in their best interests to also pursue orbital debris remediation. The first one or two companies to emerge with a successful product will have a significant advantage over competitors by being able to target the most hazardous objects in LEO for remediation. Such missions will readily garnish national and even international support because they benefit all humanity and preserve LEO for the use of future generations, use that could be lost forever if action is not taken.

StreamSat has advantages in fuel conservation, operational cost, and safety because of the concept of using ionic liquid droplets as the fuel source. A potential disadvantage to the StreamSat concept is current space laws which ban the weaponization of space. Analysis shows that droplets would not have the capability to destroy or even damage a spacecraft, but this may be difficult to prove on the world stage. Any system that can remove objects from orbit has the potential to be used to remove an operational spacecraft from orbit so any competing system would face similar political hurdles. Because StreamSat has the ability to affect numerous objects with a single spacecraft launch, it may be useful to gain the support of international partners to help quell concerns of use of the system to alter the orbits of operational spacecraft. Due to the relative simplicity of the design and lack of need to rendezvous with objects, StreamSat stands above the competition in many areas, shown in Table 4.

Competitor Analysis						
Factor	**StreamSat**	**CleanSpace One**	**Phoenix Program**	**Terminator Tape**	**Sling-Sat**	**ORION**
Fuel Conservation	Advantage	Disadvantage	Even	Advantage	Advantage	Advantage
Complexity	Advantage	Even	Disadvantage	Even	Disadvantage	Disadvantage
Cost (material worth)	Advantage	Disadvantage	Disadvantage	Even	Advantage	Advantage
Cost (operation	Advantage	Disadvantage	Even	Advantage	Disadvantage	Advantage
Political Barriers	Disadvantage	Advantage	Advantage	Advantage	Disadvantage	Advantage
Safety	Advantage	Even	Even	Even	Even	Disadvantage
Feasibility	Even	Advantage	Advantage	Disadvantage	Disadvantage	Disadvantage

Table 4. Analysis of Competitors in Orbital Debris Remediation Market

Recommendations

A successful Stream DemoSat mission would pave the way for more orbital debris remediation spacecraft that would significantly reduce the risk of future space operations. This risk reduction can be realized at a cost that is less than the cost of just one of the many high-value spacecraft expected to be lost in the coming years, if high priority hazardous objects are not removed from orbit. The need is relatively urgent as the breakup of any of the hundreds of high-priority hazardous objects in LEO could lead to a chain reaction in which other objects are destroyed and an altitude band of LEO rendered permanently unusable. StreamSat can be a shining example of preservation of the space environment for future generations while reducing the cost of space operations.

USAFA received an $8,000 grant from NASA that was used for technology development and testing. Funding is currently being sought for development of hardware for use in a demonstration mission either as a stand-alone spacecraft or as a payload on a spacecraft. The cost to build a spacecraft payload that would refine models of droplet charging and then demonstrate remediation of an object is estimated at $2 million. This estimation includes to $1.3 million delegated to labor, $500,000 to equipment, and $100,000 to launch associated costs but assumes the host spacecraft has funding for the launch. Due to current fiscal limitations in the U.S. government and the international benefit of StreamSat, it may be useful to seek foreign government collaboration and support. Officials within the space programs of Brazil, Chile, and Singapore have expressed interest in collaborating in the development of this technology and visiting researchers from Singapore have contributed to the program.

Another possible source of funding to support the development of StreamSat is the commercial satellite insurance industry which has a vested interest in preserving LEO for spacecraft operations and limiting the number of claims caused by debris impacts. Records indicate that in 2008 the annual average of satellite insurance premiums was $20 million. A system that reduces future claims and costs only tens of millions of dollars is likely worth the investment to this industry that is dominated by a single insurance company, Lloyds of London. Insurance company investment is even more likely if it is made in tandem with government support or in tandem with telecommunications companies who stand to benefit from less orbital debris due to reduced replacement costs in the future.

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